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DATA ASSIMILATION AND MODEL EVALUATION EXPERIMENTS - NORTH ATLANTIC BASIN

PRELIMINARY EXPERIMENT PLAN

Edited by

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The University of
Southern Mississippi

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ABSTRACT

A preliminary experiment plan is presented for Data Assimilation and Model Evaluation Experiments - North Atlantic Basin (DAMÉE-NAB). The plan describes the approach to implement a comparative environment in which to assess numerical ocean model nowcast/forecast capabilities and data assimilation methods and techniques. Goals are stated which provide direction for the long term, the next five years, and specifically for the next two years. A design of the experiment is outlined in terms of domain, data requirements, and measures of performance. The plan will be refined over the next year and will be allowed to evolve as the experiment proceeds. A brief description by participants of models and data assimilation methods are included.

I. INTRODUCTION

Data Assimilation and Model Evaluation Experiments - North Atlantic Basin (DAMÉE-NAB) provides a forum for discussions and information exchange on results from assessments of the nowcast/forecast capabilities of high-resolution ocean modeling, including data assimilation. These assessments address fundamental research issues in coupled, multi-scale modeling and are relevant to Navy needs on synoptic time scales (2-3 weeks). DAMÉE-NAB explicitly focuses on the ocean mesoscale which is typically 100-1,000 km and from a week to months in space and time scales. Assessments will be conducted (Table 1) in two time windows, with each assessment based on different datasets. The first time window is GEOSAT extended repeat mission (ERM) (1987-1989), the second will be chosen during the TOPEX/POSEIDON mission. DAMÉE-NAB will begin by assessing the climatological (statistical) behavior of participating models. Subsequent studies will explore the nowcasting/forecasting capabilities of the model systems, including data assimilation.

II. BACKGROUND

There are four principal components of the DAMÉE-NAB comparative environment. The first, and the most challenging, is data. Data acquisition, quality control, analysis, and processing are central issues that require extensive efforts. A DAMÉE (DATA) group can be geographically diverse, each contributing components of the desired end products to a common point for final assemblage, analysis, and distribution. Data Assimilation and Model Evaluation Experiments - Gulf Stream Region (DAMÉE-GSR) has shown that the quality of the initialization data is the primary factor in the capability of an ocean model to forecast accurately. Results indicate that assimilating data types used in the initialization will substantively improve the forecast skill of a model. Model-data assessments require long-term averages to develop stable statistics as well as data to support the explicit needs of models as they generate the nowcast and forecast. These data, usually multiparameter, require significant preprocessing and analysis to prepare them for use in a quantitative assessment.

The second component is the models (including data assimilation schemes) that are participating in an experiment. The modeling groups bring their model into an experiment, prepared to make the assessment and communicate results to the other participants. A third DAMÉE component is the design of experiments put forward by modeling groups. It consists of agreed-upon factors defining: the geographical extent of the experiment; data and data types to be used; the amount of preprocessing and analysis to be done; and the minimal common measures of model performance each modeling group will use. This includes agreement on how these results are to be presented so that each can understand the other's results. The fourth component is information flow. It is essential that frequent and in-depth information be exchanged between the groups of a DAMÉE. This can be achieved through technical meetings, newsletters, and other forms of collegial interactions.

III. GOALS

A. Overall Goal

Contribute to the development of a global ocean nowcasting capability with basin-wide forecasting skill that provides descriptions of the three-dimensional ocean structure, the locations of mesoscale features such as eddies and ocean fronts, and environmental definition with accuracy superior to climatology, persistence, and damped persistence.

B. Interim Goals (Years 1 and 2)(See Table 1)

Model climatology experiments (C1): Each group engaged in DAMÉE-NAB will establish the climatological behavior of their prognostic circulation model with respect to a specified list of "known" properties of the North Atlantic subtropical gyre.

Forecast experiments (F1): One or more forecast experiments (and associated initialization, assimilation and verification datasets) will be agreed upon in Year 1. The target domain is the North Atlantic subtropical gyre during the period of 1988-90, which corresponds to a significant portion of the western North Atlantic SYNOP observational period. The DAMÉE-NAB data group will identify all available datasets from this period. The emphasis in these forecast experiments will be on synoptic-time-scale prediction (i.e., weeks to months).

C. Longer-term Goals (5 years)

Establish basin-scale predictive capabilities of each DAMÉE modeling system relative to persistence, climatology and damped persistence.

Investigate the sensitivity of mesoscale forecasts to variations in the climatological measures; e.g., is getting North Atlantic Deep Water (NADW) production important to short-term mesoscale forecasts, etc.

As much as possible, identify strengths and weaknesses common to different model classes and assimilation methods; e.g., geopotential, sigma and isopycnal coordinates; low- and high-order algorithms; ad hoc versus sub-optimal assimilation methods; alternate embedding techniques; etc.

Explore and implement procedures for producing coupled models and forecasts of the North Atlantic and its adjacent coastal regions.

IV. EXPERIMENT DESIGN

A. Domain

Nominal domain for initial experiments C1 and F1 will be the North Atlantic between 9°N-47°N. Larger domains (e.g. the CME domain) may be considered at the discretion of individual DAMÉE groups. The nominal resolution is 10 to 20 km; however, specific resolution requirements will be dictated by the initialization, assimilation, and verification datasets eventually chosen for the experiments. Vertical resolution will be chosen independently by each group, as required for each model. Bathymetry data for the region of interest will be derived from ETOPO-5 (5 min) and the NOS (15 sec) gridded coastal dataset. Suitable software will be made available to interpolate to lower resolution grids by the data group. Boundary conditions and/or domain nesting strategies will be chosen at the discretion of each group.

B. Data

The DAMÉE-GSR database consists of satellite infrared imagery, GEOSAT altimetry, and (A)XBT/CTDs from numerous sources including SYNOP during the data-rich years of 1987 and 1988. The 6-week duration test case developed for DAMÉE-GSR was constructed by overlaying the datasets in a Gulf Stream region Geographic Information System (GIS) and generating approximately weekly analyses of the Gulf Stream North Wall and ring locations. The May-July time period was chosen because it provided the most cloud free coverage of the Gulf Stream during the entire GEOSAT Exact Repeat Mission. The moored SYNOP data was not available at the time the test case was prepared, but has been separately acquired by several investigators for use as an independent dataset.

Preliminary efforts at extension involved similar datasets. The JPL global archive of satellite-derived sea surface temperatures is accessed. It contains weekly average SST values compiled separately for day and night images in two formats, one that retains only the cloud-free pixels and another in which the missing pixels are filled in with interpolated values. There appears to be very little difference in the day versus night cloud-free pixel values, except that the daytime images typically contain more data. The GEOSAT geoid used for DAMÉE-GSR was extended to the western North Atlantic and verified using newly-released NAVOCEANO AXBTs. The NODC XBT dataset on CD-ROM was accessed; and despite the greater than 2600 XBTs in the NAB during the DAMÉE-GSR 1988 test case, virtually none of the hydrographic observations used in DAMÉE were archived by NODC.

Subsequent discussion concentrated on the definition of an evaluation time period for DAMÉE-NAB and additional data sources. The evaluation domain for the first stage of DAMÉE-NAB will be 9°N-47°N from coast to coast, based

on the discussions of preliminary model results. The "SYNOP time period" was adopted for the evaluation time period because of the vast amount of Gulf Stream in situ data now available from that experiment and the availability of a working altimeter. The SYNOP experiment covers late 1987 through early 1990, while GEOSAT altimetry is available from late 1986 through mid 1989. Continuous AVHRR imagery coverage during this time period is presently available from the existing JPL global archive and will soon be available as one of the improved NASA Pathfinder datasets.

Therefore, additional climatological datasets that will be provided for the first stage of DAMÉE-NAB will include:

1. The Lozier/Owens/Curry climatology.
2. Climatologies of atmospheric forcing (wind stress, heat and freshwater fluxes).
   a. derived from ECMWF products
   b. Hellerman-Rosenstein, Isemer-Hasse
   c. ECMWF heat flux (Climatologies formed from these data showed severe aliasing problems in the solar radiation. NRL removed the alias and made the 1985-89 ECMWF heat fluxes usable and formed daily averages, but, it is still basically the ECMWF heat flux product.) (This includes a 1985-93 daily time series.)
3. Sea surface temperature climatology
4. An improved bathymetry (ETOPO-5 with coastal corrections and augmentation from the NOAA 15 second gridded data). A detailed report on these datasets will be available by Sept. 30, the datasets themselves will be available by the end of the year.

Additional in situ data collected by investigators from other countries is known to exist but has not been assembled. The data group will produce an inventory of these datasets from the SYNOP time period, that could be made available for DAMÉE-NAB, and will begin collecting the easy ones.

A computerized card catalog (oceandb or MOSAIC) containing a description, location and availability of the datasets will be compiled and made available to all participants.

C. Measures

A wide range of evaluation measures are under consideration. Once the evaluation datasets have been identified, specific measures of performance will be chosen. There should be some interannual time-dependent evaluations to test nowcasting ability, without ocean data assimilation to investigate deterministic vs. nondeterministic responses. Timeframes of interannual simulations should be 1985-latest available forcing, and interannual validation should be 1986-latest available forcing.

How well and under which conditions can the models replicate the features of the climatological database.

- mean and seasonal cycle of transport through the Florida Strait
- mean path and envelope of the Gulf Stream
- path and strength of the Deep Western Boundary Current
- horizontal distribution and amplitude of eddy kinetic energy
- mean transport and seasonal cycle east of Abaco (Bahamas)
- eddy shedding period, ring propagation speed and EKE or SSH variability distribution in the Gulf of Mexico
- comparisons with time series at sea level stations
- comparisons with SSH anomaly maps from satellite altimetry

(The numerical simulations conducted to compare with these climatological measures will be free, initial value problems - i.e., no assimilation of data will be used at this stage. The nominal integration time for these experiments is 5-10 years.)

V. NEEDS

A. Operational

Fleet Numerical Meteorology and Oceanography Center (FNMOC), as one of the primary operational environmental processing centers in the nation, is very interested in comparisons of advanced numerical analysis and ocean forecast models leading to model improvements. Emphasis on coastal 3-dimensional nowcasting and forecasting is extremely relevant with the Navy's new focus on the littoral. FNMOC and its sister organization, the Naval Oceanographic Office, are becoming increasingly involved in supporting operations in the littoral.

FNMOC operates fully-automated global and regional meteorological and oceanographic (METOC) models. The global meteorological model, the Navy Operational Global Atmospheric Prediction System (NOGAPS), has recently been upgraded to T159 spectral resolution, which corresponds to horizontal grid spacing of about 80 km. The FNMOC regional meteorological model, the Navy Operational Regional Atmospheric Prediction System (NORAPS), is currently operated for several regions with grid spacing varying from roughly 20 to 40 km. A number of global and regional oceanographic models are in operation at FNMOC. These include the Optimum Thermal Interpolation System (OTIS) data assimilation model, the Thermodynamic Ocean Prediction System (TOPS) mixed-layer model, the Data Assimilation Research and Transition (DART) dynamic model, and the Third-Generation Wave Model (WAM). Grid resolutions for these models generally range from about 100 km for global implementations to 20-25 km for regional implementations.

With the Navy's warfighting focus shifting to the littoral regions of the world, FNMOC's METOC modeling focus is shifting accordingly. New model implementation efforts at the Center will emphasize the littoral, with short-term efforts focused on NORAPS, OTIS, WAM, and the Princeton Ocean Model (POM). In the longer term, however, the major effort will be directed toward implementation of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) model, which will ultimately combine the functionality of NORAPS, OTIS, WAM and POM. Only such a fully integrated sea-air-land model can provide the seamless sea-air-land products required for support of joint littoral warfare. Global and basin-scale METOC models will still be required, however, to provide the necessary open boundary conditions for these automated regional littoral models. See Plante and Clancy (1994) for a more detailed discussion of current and planned FNMOC METOC modeling efforts.

Cooperation with DAMÉE will add significantly to the development and enhancement of ocean prediction capabilities and systems introduced to the Fleet. FNMOC shares a number of interests with DAMÉE, including data assimilation and modeling. Models developed by NRL/Monterey and NRL/Stennis

Space Center are delivered to Fleet Numerical for adaptation to operations. Understanding the strengths and weaknesses of the Navy models relative to other models is invaluable in introducing improvements.

B. Research

There are still many challenging and fundamental scientific questions to be addressed in ocean nowcasting/forecasting. The time and space scales with which DAMÉE-NAB is most concerned is the mesoscale. We must recognize that broader issues do exist that are not directly relevant to this and that there are still others that are related but outside the scope of DAMÉE-NAB. Principal components in the fundamental science questions are related to the following:

How well and under which conditions can the models replicate the features of the climatological database.

- mean and seasonal cycle of transport through the Florida Strait
- mean path and envelope of the Gulf Stream
- path and strength of the Deep Western Boundary Current
- horizontal distribution and amplitude of eddy kinetic energy
- mean transport and seasonal cycle east of Abaco (Bahamas)
- eddy shedding period, ring propagation speed and EKE or SSH variability distribution in the Gulf of Mexico
- comparisons with time series at sea level stations
- comparisons with SSH anomaly maps from satellite altimetry

Data Assimilation

- realistic field estimation
- real oceanic fields

Physical Field Estimation

- DAMÉE-NAB (i.e. nowcasting/forecasting oceanic fields and how "well" we do it)

Climate and Global Change

- coastal ocean and coupled coastal/deep sea regions

Interdisciplinary Modeling

- coupled physical/biological/chemical models (feasible because we can now attain realistic field estimations by assimilating real oceanic fields)

There are multiple interactive scales over an ocean basin (e.g. the North Atlantic). Understanding how good a physical field estimation is for the meso-scale may require knowledge of how the interactive scales are related to the quality of the estimation.

As we consider the coupling of models and domains, we recognize that there are one- and two-way transfers of information; and there are challenging issues for data assimilation schemes.

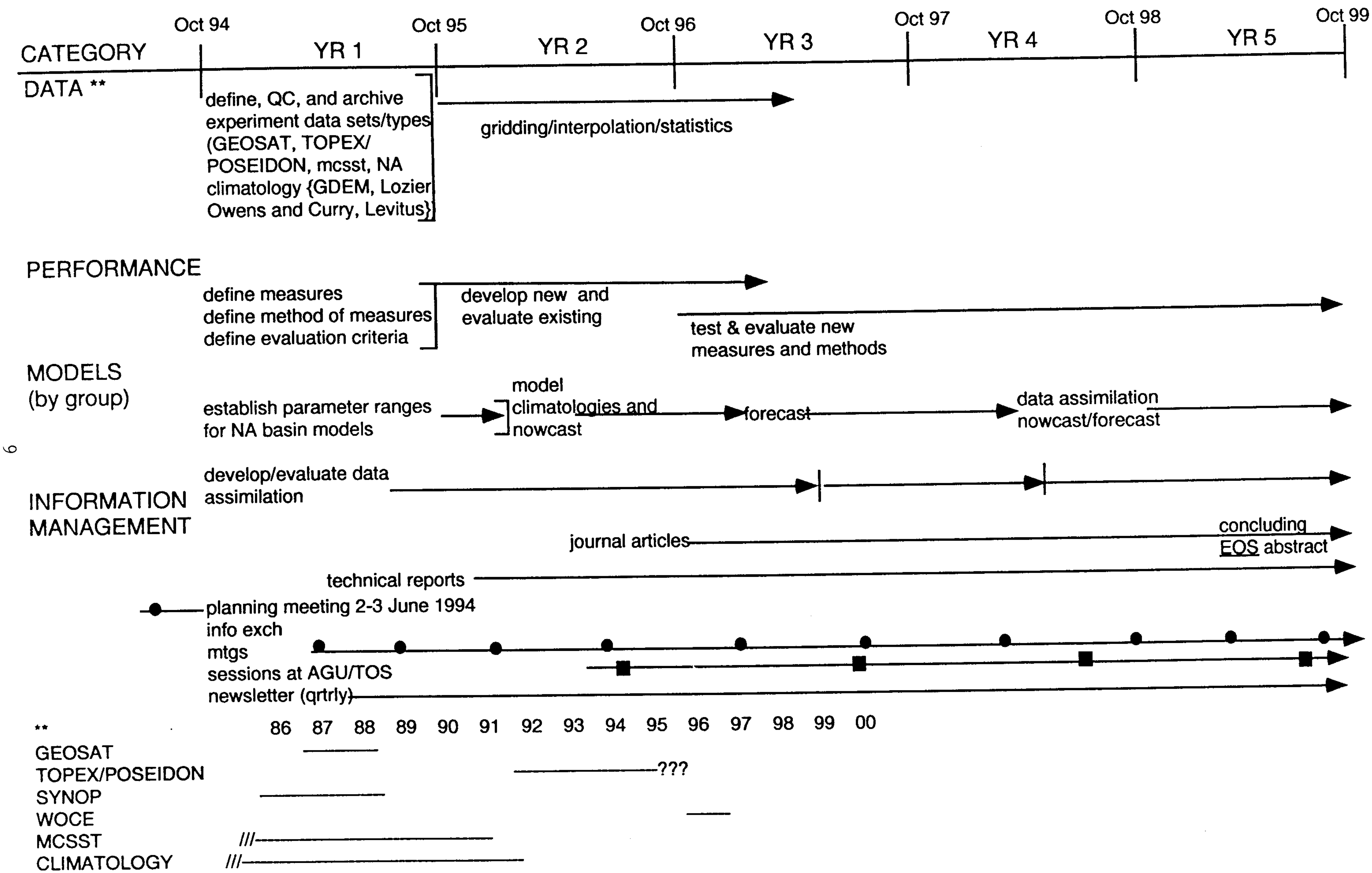

Table 1: DAMÉE-NAB Schedule of Events

VI. PARTICIPANTS AND ORGANIZATIONAL STRUCTURE

Much of the DAMÉE-NAB organizational structure is based on interaction and exchange of information. As suggested in Table 1, there will be periodic information exchange meetings which will serve as the forum for discussions and refining the experiment plan. Additionally, periodic newsletters will be issued based on participant contributions. The overall scientific directions are provided by Dr. William J. Schmitz. There are six modeling groups who are presently participating. DAMÉE-NAB does not include or exclude any modeling group. In addition, there is a group that provides data support to the modeling groups. Presently, the participants in DAMÉE-NAB are:

Mr. Valentine Anantharaj
Dr. Hernan Arango
Dr. Mike Bell
Dr. Eric Chassignet
Mr. Mike Clancy
Mr. Jim Corbin
Dr. Jim Cummings
Mr. Webb deWitt
Dr. Tal Ezer
Dr. Manny Fiadeiro
Prof. Michael Ghil
Dr. Scott Glenn
Dr. Dale Haidvogel
Mr. Patrick J. Hogan
Dr. Harley Hurlburt
Dr. Kayo Ide
Dr. Mohamed Iskandarani
Dr. C. Aaron Lai
Dr. Susan Lozier
Dr. Paul May
Prof. George Mellor
Mr. Bob Peloquin
Mr. Ken Pollak
Dr. Paola Rizzoli
Prof. Allan Robinson
Prof. Bert Semtner
Ms. Robin Tokmakian
Ms. Tammy Townsend
Cdr. Scott Sangathe
Cdr. Martin Sauze
Dr. Bill Schmitz
Dr. Ziv Sirkes
Mr. Bob Willems

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Lozier, M.S., W.B. Owens and R.G. Curry, 1994: "The climatology of the North Atlantic." Progress in Oceanography, in press.

Plante, R.J. and R.M. Clancy, 1994. An Overview of Operational Prediction Capabilities at Fleet Numerical Meteorology and Oceanography Center. Proceedings of the MTS '94 Conference, 7-9 September 1994. Washington, DC, Marine Technology Society, 1828 L Street NW, Suite 906, Washington, DC 20036, pp. 352-358.

VII. MODELS/DATA ASSIMILATION

A. Basin-scale Ocean Circulation Modeling on Global, Non-uniform Finite Element Grids

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Rutgers University
New Brunswick, NJ

The present work is part of an ongoing effort to build and to apply more accurate and efficient models of the large-scale ocean circulation. Long-term objectives are: (1) to produce a new generation of basin-scale ocean circulation models based on the spectral finite element (SFE) technique; (2) to couple the resulting basin-scale model to higher-resolution, sub-basin-scale models for (e.g.) the coastal boundary layers; and (3) to apply the resulting nested suite of models to studies of basin-scale dynamics, data assimilation, and prediction.

A shallow-water SFE code has now been implemented and tested (Iskandarani et al., 1994). It has been shown that judicious choice of spectral expansion functions (Legendre polynomials), numerical quadrature and time-stepping technique are essential to produce a computationally-competitive model. A wide variety of numerical experiments have been conducted to assess the performance of the model and to compare its behavior with that of more established codes (e.g., the Sadourney shallow water model). Analytic test problems confirm the faster-than-algebraic convergence of the model.

A potential advantage of the spectral finite element technique, which is currently being evaluated, is the prospect of conducting high-resolution basin-scale simulations of (say) the North Atlantic Ocean on a global, nonuniform grid. (An example of an SFE grid with enhancement in the Pacific Ocean is given in Figure 1.) The possible advantages of such an approach include the complete absence of any open boundary conditions, known to cause troubles in past basin-scale experiments such as the CME. The global grid incurs a computational penalty, of course; however, the extra cost is typically quite small. (For example, consider a North Atlantic model covering one tenth of the global ocean with a 10 km grid; then the remainder of the world's oceans can be attached at an average resolution of one degree for an additional 9 percent in computational resources.) Preliminary experience with these global, nonuniform grids is that they perform well despite the large variations in grid spacing involved. Figure 2 shows an instantaneous interface displacement map from a multi-year simulation using the reduced gravity model on the global grid shown in Figure 1.

A shallow water model is being aggressively pursued proceeding toward a three-dimensional version using primitive equations. Design criteria include the accurate representation of the effects of topography and of the surface, coastal and bottom boundary layers, the development of time-stepping procedures for the efficient treatment of the internal and external modes on an unstructured grid, and the utilization of high performance (parallel) computing platforms to enable affordable basin-scale integrations. The domain decomposition philosophy underlying the spectral finite element technique, and the large ratio of inter-element computation to intra-element communication, suggest that these models will be well suited to the parallel computing environment.

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Iskandarani, M., D.B. Haidvogel and J.P. Boyd, 1994. A staggered spectral finite element model with application to the oceanic shallow water equations. Int. J. Num. Meth. Fluids, accepted.

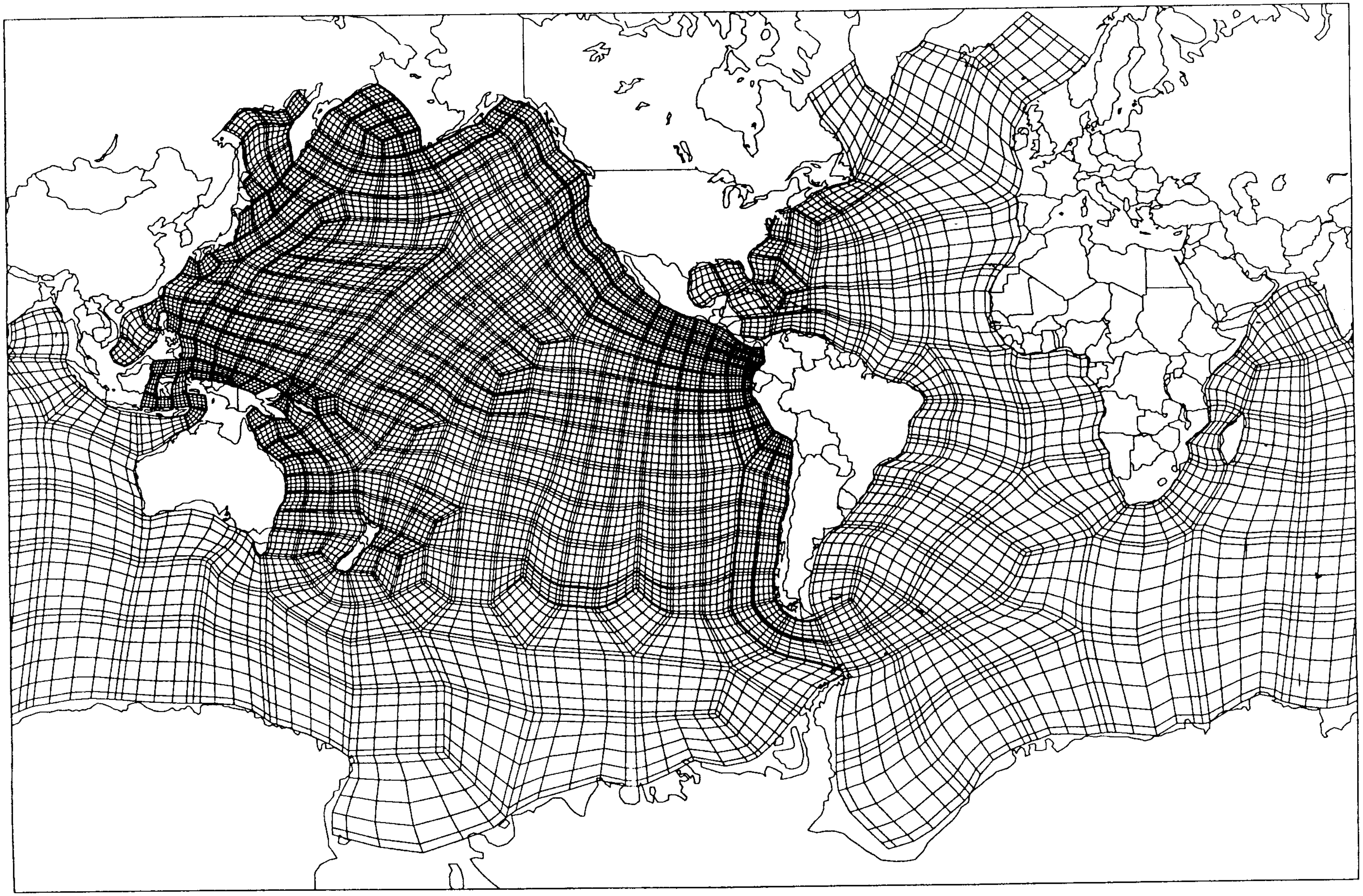

Figure 1: An example of a global, non-uniform SFE grid having enhanced resolution in the Pacific Ocean. There are a total of 464 quadrilateral elements, within each of which is a 7x7 Legendre expansion.

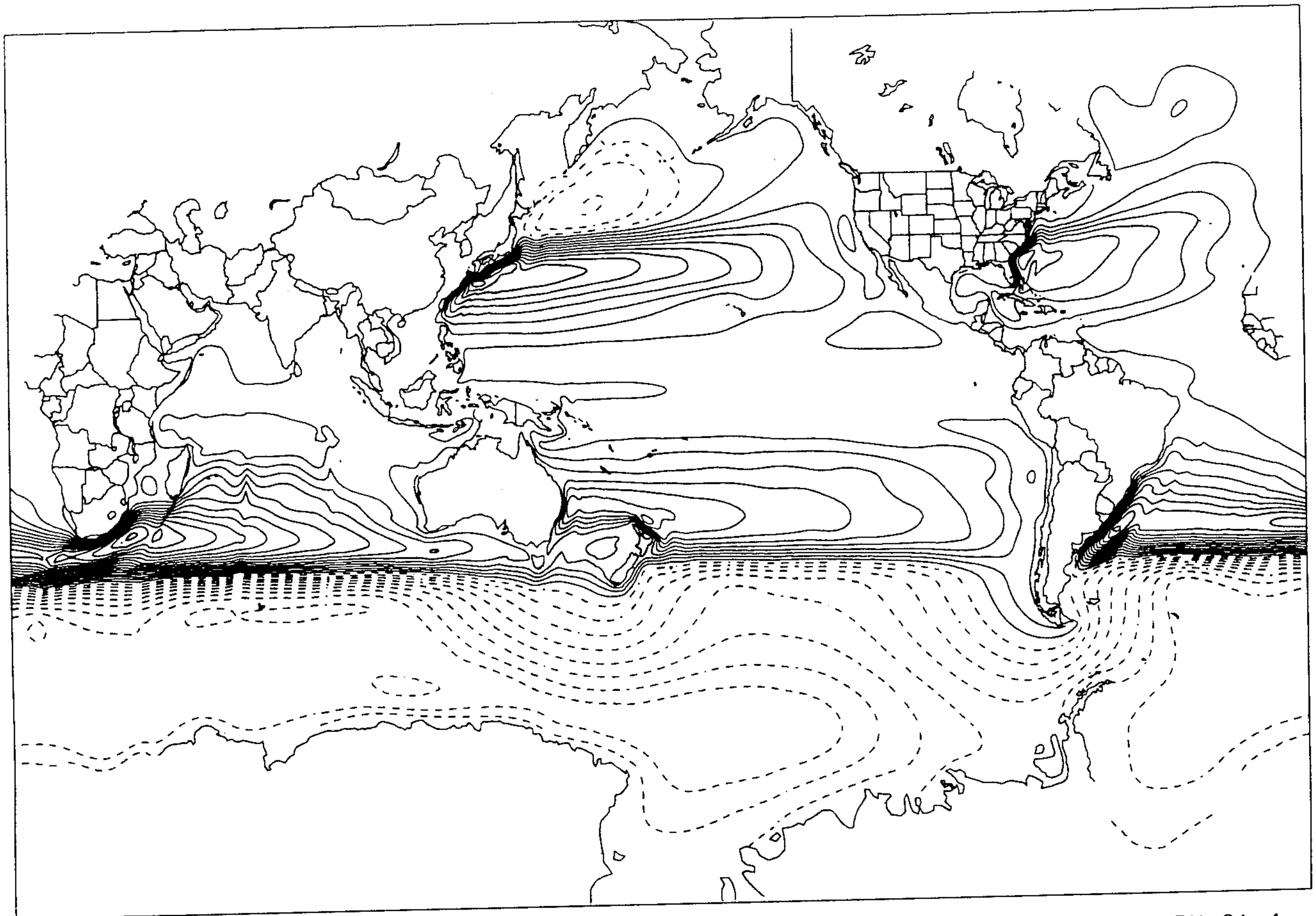

Figure 2: Instantaneous interface displacement after 40 years of integration on a world grid. The model, configured in reduced gravity with an initial thickness of 300 meters, is driven by mean monthly ECMWF winds. The contour interval is 31.4 meters.

B. Princeton's Plans for Modeling and Data Assimilation Studies in the North Atlantic

Tal Ezer and George L. Mellor
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Princeton, NJ

The Princeton Ocean Model, POM (Blumberg and Mellor, 1987) is a three-dimensional, primitive equation model with complete thermohaline dynamics, a free surface, and a turbulence closure submodel. It has a bottom following, sigma, vertical coordinate system and a coastline following, curvilinear orthogonal, horizontal coordinate system (some of the model grids used are shown in Fig. 3). In the past few years, modeling and data assimilation studies in the western North Atlantic were part of the Data Assimilation and Model Evaluation Experiments in the Gulf Stream region (DAMÉE-GSR). Effort has focused on different aspects of the Gulf Stream dynamics (Ezer and Mellor, 1992; Ezer, 1994), evaluation of forecast and nowcast skill (Ezer et al., 1992, 1993), and the development of data assimilation techniques (Mellor and Ezer, 1991; Ezer and Mellor, 1994a). The assimilation uses an efficient optimal interpolation method and the projection of satellite-derived surface data into the deep layers. Recent studies demonstrate the potential for improving nowcast skill by optimally combining altimetry and SST data and the use of other data sources such as Gulf Stream position.

The modeling and the data assimilation methodology are being transferred from a research to an operational environment. As part of NOAA's coastal ocean initiative, the east coast-Gulf Stream model has been coupled (in a one-way interaction at this point) with a regional atmospheric model (ETA model). The system, known as the Coastal Forecast System (CFS), was implemented at NMC in the Summer of 1993 and has been running since then in a quasi-operational mode, producing daily forecasts of oceanic fields such as sea level, temperature and currents. Experience in operational coastal forecasting will also be useful to the Navy efforts, since POM is being used by the Navy in other coastal regions.

The plan is to continue the efforts in the development of data assimilation techniques by including other data sources and to extend the mesoscale nowcasting/forecasting from regional to basin-scale models. Applications of the Princeton model to basin-scale simulations are now underway for climate studies (Ezer and Mellor, 1994b). The model seems to produce realistic thermohaline circulation and meridional heat transport, which are often underestimated by z-level models such as the CME. These studies, which started as part of the Atlantic Climate Change Program (ACCP), will support the new initiative to continue the DAMÉE project for the North Atlantic Basin (DAMÉE-NAB). The plans are to first focus on several aspects of the general circulation, with special emphasis on problems such as Gulf Stream separation,

which has been previously studied in detail using the regional model (Ezer and Mellor, 1992). Then, efforts will be focused on nowcast/forecast mesoscale variabilities in a basin-scale model, following the data assimilation methodology developed during the regional studies. The use of different model grids (Fig. 3) will help in establishing open boundary conditions, where models of larger domains will supply boundary conditions to regional models.

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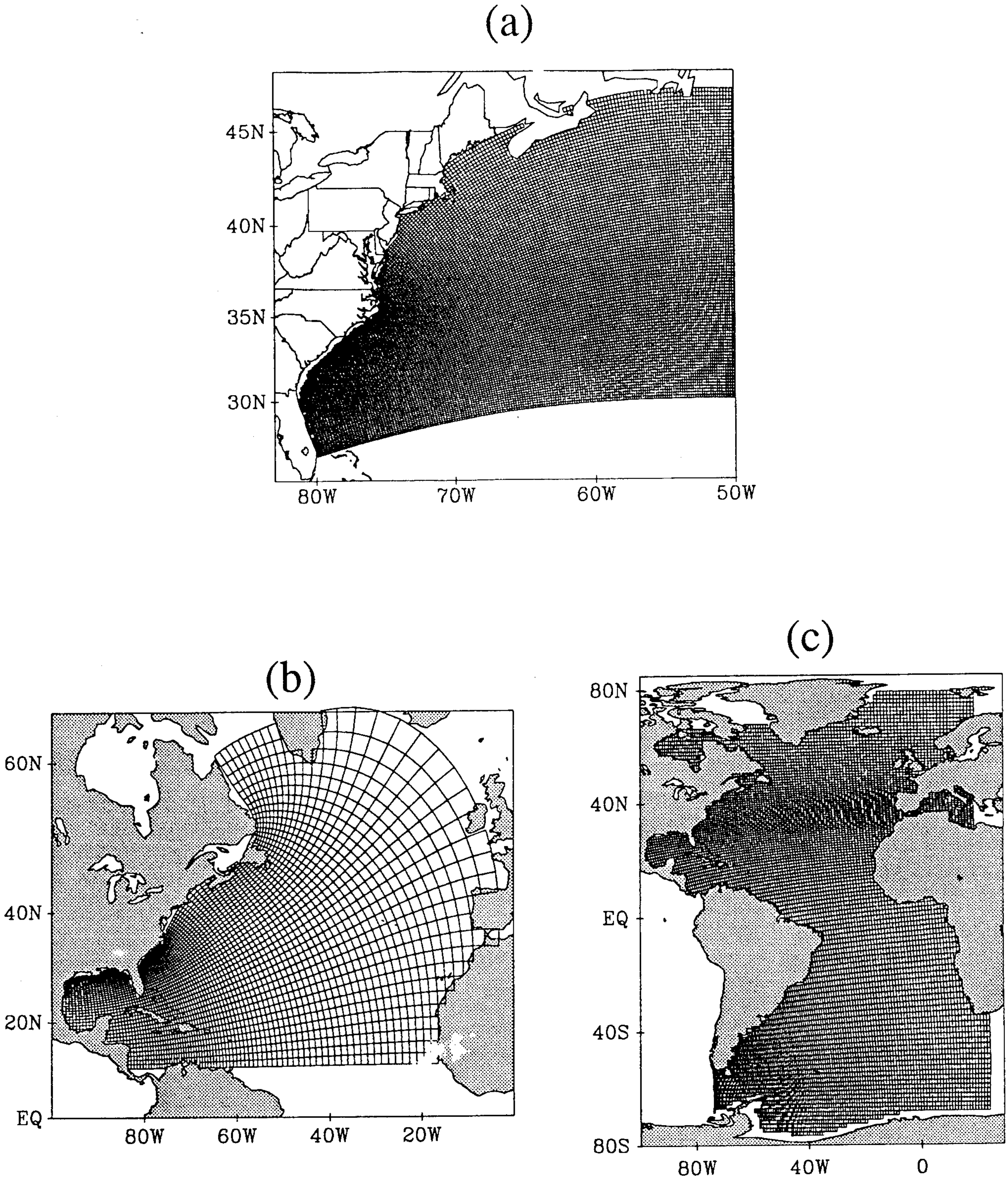

Figure 3: Different model grids used for the Atlantic Ocean.

C. Inverse Modeling in the North Atlantic Ocean

Paola Malanotte-Rizzoli
Massachusetts Institute of Technology
Cambridge, MA

All the modeling simulations of the large-scale thermohaline circulation of the North Atlantic exhibit serious weaknesses, even those carried out under the most realistic conditions in the CME (Community Modeling Effort) by Holland and collaborators at NCAR, by Böning and collaborators in Kiel and by Maier-Reimer in Hamburg. These weaknesses are due to a variety of causes, ranging from deficiencies in the (T,S) climatologies used as initial conditions or in the surface forcing functions to deficiencies in the circulation model itself, such as a bad specification of open boundary conditions or poor parameterizations of subgrid scale processes. Such deficiencies lead sometimes to major discrepancies between the model simulation and the related observational evidence. One such example is the northward heat transport in the North Atlantic that is vastly underestimated in the great majority of simulations, leading to a meridional distribution that is half the observed one in the latitude band 0° to 40°.

One way of trying to remedy the weaknesses of modeling prognostic calculations relies, therefore, in improved parameterizations of sub-grid scale processes, better formulations of surface and lateral boundary conditions, etc. A second and very promising way to obtain better simulations of the North Atlantic thermohaline circulation is through the use of inverse methods that constrain the model dynamics directly with the available data and, therefore, may correct the model deficiencies by best fitting the model evolution to the data.

At MIT, together with a postdoctoral associate, Dr. Lisan Yu (supported by a NASA grant), an adjoint code has been developed for the GFDL model which is now operational. This GFDL plus adjoint configuration is not the one used by Tziperman et al. (1992) or Marotzke and Wunsch (1993). These applications, used a simplified version of the GFDL plus adjoint codes, steady and linearized (i.e., diagnostic) in the horizontal momentum equations which prevented the models from being able to cross the equator. MIT has developed the adjoint for the time-dependent, fully nonlinear GFDL code with exactly the CME configuration, from l5°S to 65°N, 30 levels in the vertical, same bottom topography, same northern and southern sponge layers to mimic water mass formation in the polar seas and interaction with the southern ocean. Fig. 4a shows a simulation carried out in the CME configuration with the coarse resolution of 1 x 1.2, and compares the meridional thermohaline cell obtained in a purely prognostic calculation and through the adjoint. Specifically, Fig. 4b shows the result of the prognostic calculation, the zonally-integrated flow in Sverdrups (Sv = 106 m 3/sec) from l5°S to 65°N in latitude. The sinking at high

latitude (60°N) is quite evident, leading to the formation of North Atlantic Deep Water (NADW) with a production rate of ~23 Sv, too strong compared to the average estimated production rate of ~16 Sv. This excess rate is due to the fact that the winter winds, stronger than the yearly average, are used. At depths of ~4000 m, the cell of Antarctic Bottom Water (AABW) that protrudes northward below the NADW is also reproduced. Aside from the excessive production of NADW, the major deficiency of the meridional thermohaline circulation, a deficiency common to many such calculations (Böning et al., 1994), is that the meridionally-protruding NADW cell is confined to ~20°N. Only about 10 Sv reach the equator, compared to the observational figure of ~13-14 Sv (Schmitz and McCartney, 1993). The confinement of the NADW cell is due to the strong upwelling observed between 20°N and 30°N that is found in the model in the region shoreward of the Gulf Stream. The strong upwelling is also responsible for the reduced northward heat transport characteristic of such calculations. Fig. 4a shows the corresponding meridional thermohaline circulation estimated through the adjoint, forced by the winter Hellerman and Rosenstein winds but now consistent with Levitus climatology. The NADW cell is now much more realistic, with an overall production rate of ~16 Sv; and it protrudes southward much more significantly, with ~2/3 of the production rate now crossing the equator. This more realistic configuration of the NADW thermohaline cell is due to the elimination of the strong upwelling at 30°N, evident in Fig. 4b, since this upwelling is not consistent with the Levitus climatology; and the adjoint minimizes the misfit between the model and the data.

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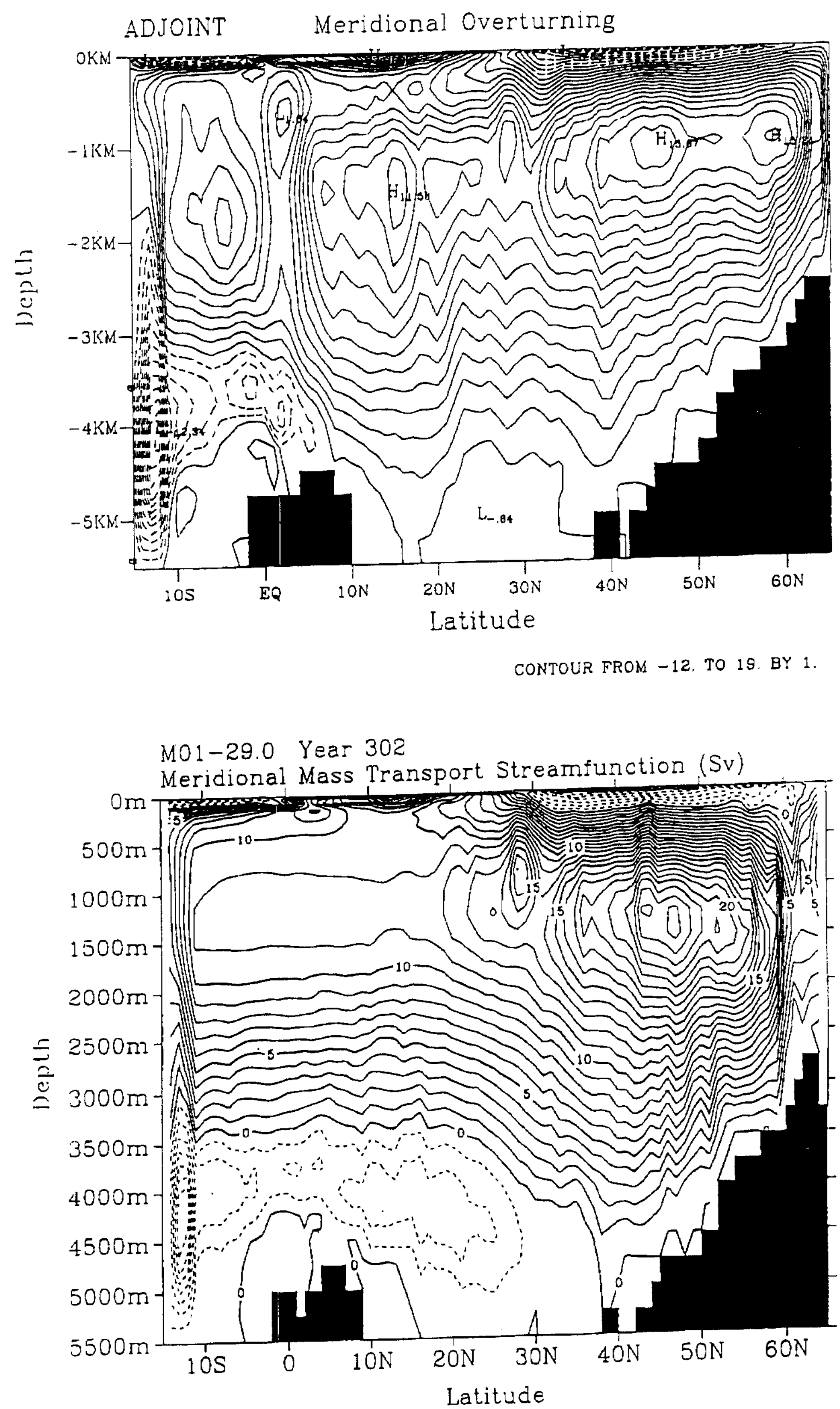

Figure 4: The meridional thermohaline circulation of zonally integrated flow computed (a) by the adjoint method (upper), and (b) Prognostically (lower).

D. The Miami Isopycnic Coordinate Ocean Model (MICOM)

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The trait common to so-called "layer" models such as the Miami Isopycnic Coordinate Ocean Model (MICOM) is that they reverse the traditional role of depth as an independent variable and density as a dependent variable. The argument has been made that of all numerical schemes used for transporting thermodynamic variables in 3-dimensional ocean models, those relying on isopycnic discretization (constant density layers) will come closest to accomplishing the transport without introducing spurious diabatic effects. This, ultimately, is the reason for investing in the development of isopycnic general circulation models.

The Miami modeling group is presently conducting a high-resolution simulation of the circulation in the Northern and Equatorial Atlantic as part of a multiyear, multi-institutional series of eddy-resolving baseline simulations of the wind- and thermohaline-driven large-scale ocean circulation. The first experiment in this series was completed a few years ago under the heading "Community Modeling Experiment" (CME) at the National Center for Atmospheric Research (NCAR) by F. Bryan and W. Holland (referred to below as the NCAR run); they chose for this work the primitive equation model developed at the Geophysical Fluid Dynamics Laboratory (GFDL) by K. Bryan, M. Cox, and A. Semtner. The purpose of followup experiments such as the present one is to explore to what extent differences in model physics and numerical discretization affect the outcome of the simulation. The ultimate purpose of this work, of course, is to improve the accuracy of ocean models.

A non-eddy-resolving (0.9 degree mesh) experiment which uses 16 layers and matches both the CME domain (15°S to 65°N) and CME forcing (referred to as the Miami run) has been carried out to 20 years. Configuring the model for the CME comparisons was complicated by the fact that the Levitus (1982) dataset had to be transformed to a piece-wise constant (stairstep-like) vertical density profile for model initialization and lateral boundary forcing at the northern and southern walls. In the course of this work, static instabilities present in the original data had to be removed, and a transform scheme that preserves the vertically-integrated density in each grid column had to be developed.

Matching the CME's prescription of surface freshwater flux in terms of a surface salinity nudging toward Levitus (1982) climatology turned out to be another nontrivial matter. Relaxing salinity in the upper 35 m of the water column, as is done in the GFDL model, is not feasible in the isopycnic model whose uppermost model layer may vary in depth between 20 and 2000 m. The procedure finally adopted infers the surface salinity flux from the original CME nudging term formulated for the fixed vertical grid and uses this flux to compute

salinity tendencies in MICOM's variable depth mixed layer. At this time, archive data from the original CME (provided by F. Bryan and W. Holland of NCAR) is being transformed into (x, y, p) coordinates. This will allow side-by-side comparisons of NCAR- and Miami-generated model results, not only in Cartesian space but also from the isopycnic perspective. Of particular interest is the determination of whether "climate drift" evidenced by a gradual redistribution of mass among isopycnic layers occurs at a different rate in the two simulations.

The barotropic streamfunction from the Miami and NCAR run for January is shown in Fig. 5 for the entire domain. While the general patterns are in agreement, one notices in the Miami run a stronger subpolar gyre and a greater transport through the Florida Straits (~12.5 versus 2.5 Sv). Viewed from the potential vorticity (PV) perspective, the equatorial undercurrent owes its existence to the fact that water drawn into the equatorial mixed layer by Ekman suction is replaced in part by laterally converging upper-thermocline water. The extent and strength of the undercurrent are likely to depend on details in the stratification. Due to the inherent ability of isopycnic coordinate models to faithfully depict processes dominated by PV conservation, the equatorial undercurrent should be expected to be a robust feature of isopycnic model simulations, provided the model is given adequate resolution in the relevant density range. This is indeed the case. Fig. 6a shows one example of the undercurrent in the Miami run. The current is seen to exhibit a meridional extent of ~v6 grid points or 600 km, a vertical extent of ~100 m, and a core speed of ~v50 cm/sec. These values do not deviate substantially from observations. A corresponding section through model fields from the 1 degree NCAR run transformed to the (x, y, p) coordinate space of the Miami output is shown in Fig. 6b. As one would expect on the basis of the above PV argument, the core speed of the undercurrent in the NCAR simulation is noticeably weaker.

The fact that the real-basin version of MICOM is time-integrated in totally explicit fashion, (i.e., it does not require the solution of elliptic partial differential equations) makes the model an attractive test object for massively-parallel processors (MPPs). This has led to the installation of the model on two of the leading MPPs, Thinking Machines' CM-5 and CRAY's T3D. Maintaining a still-evolving model code in several programming languages can be problematic as programs written in standard Fortran presently do not run well on MPPs. Collaboration with Dr. M. O'Keefe (U. of Minnesota) and the Pittsburgh Supercomputer led to an 11-layer version of the model (0.225 degree mesh or 512 x 512 x 11 grid points), covering the Atlantic between 25°S and 65°N and forced by wind stress, air temperature and humidity from the Comprehensive Ocean-Atmosphere Data Set (COADS) in combination with precipitation and net radiation from the Oberhuber atlas. According to Dr. M. O'Keefe, a 20-year 0.1125 degree simulation (12 km mesh size at the equator,

decreasing to 7 km at 60°N) on the T3D at the Pittsburgh Supercomputing Center should be able to be performed this Fall in about 300 hours of compute time.

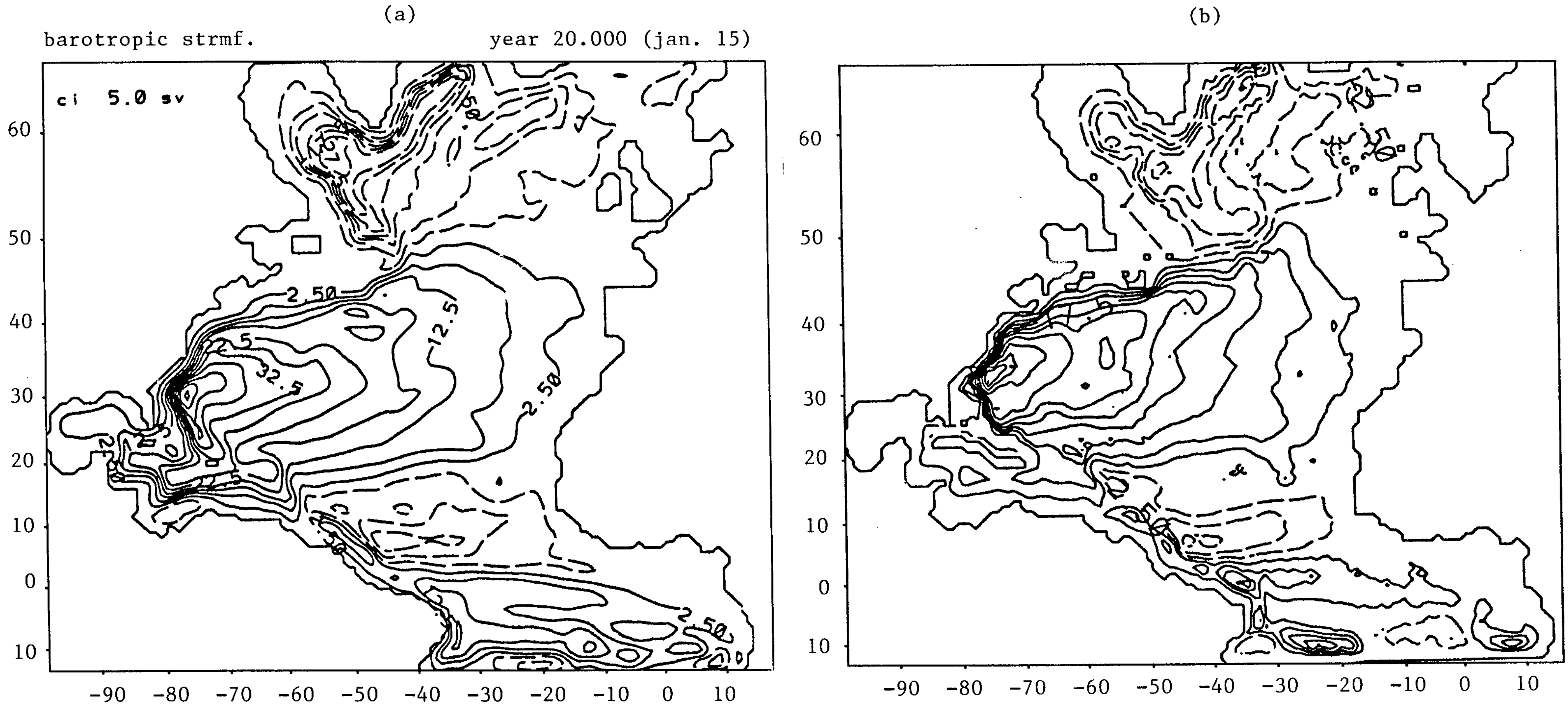

Figure 5: (a) .9 deg. Miami run and (b) 1 deg. NCAR run. Barotropic streamfunction for the entire domain. Contour interval: 5 Sv (offset from zero by 2.5 Sv). Dashed lines indicate cyclonic circulation.

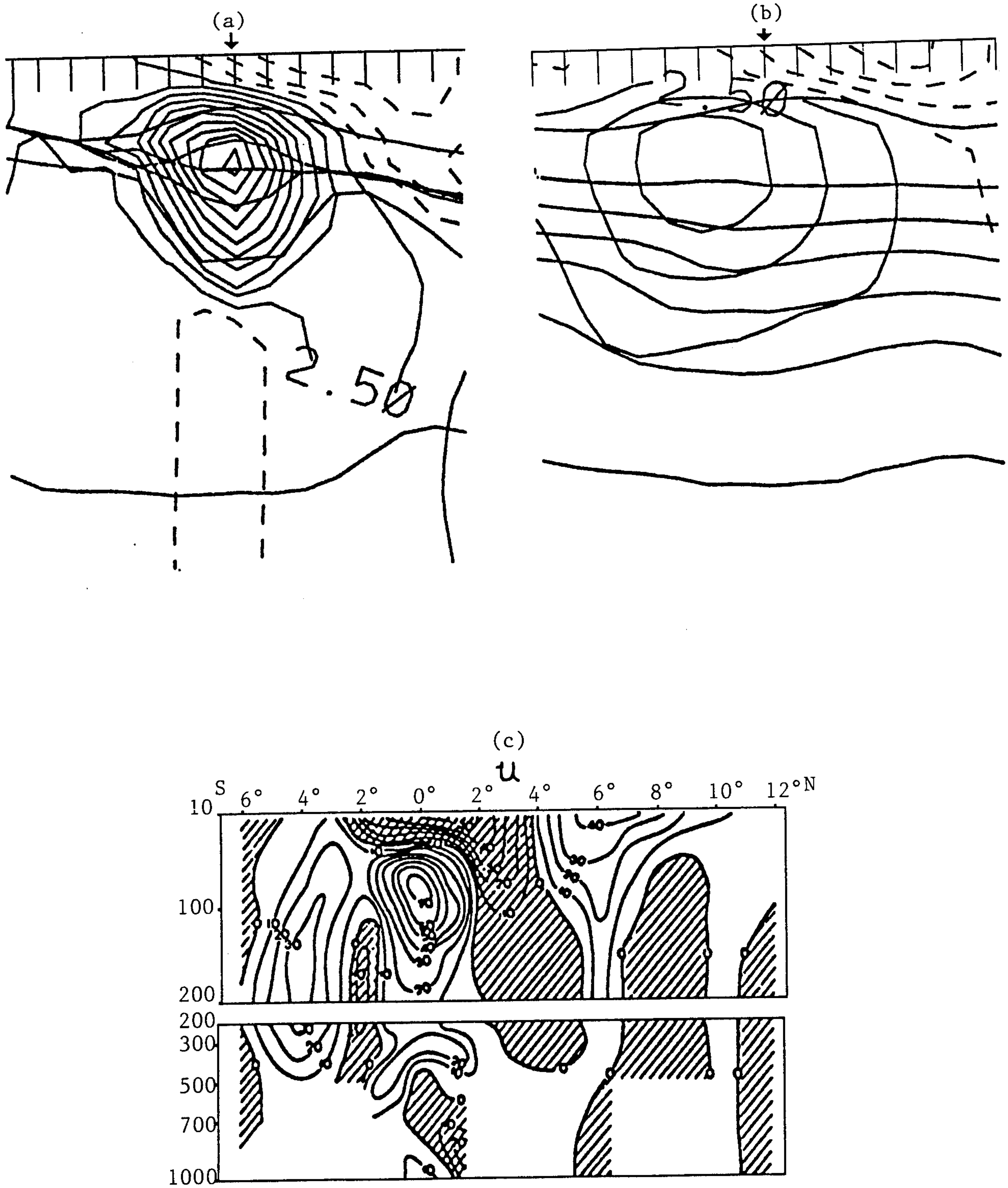

Figure 6: (a) .9 deg. Miami run and (b)1 deg. NCAR run. Vertical meridional section at 30°W (January). Arrow points to equator. Vertical scale ~v 300 m. Thick lines: layer interfaces; thin lines: isotachs. Contour interval: 5 cm/sec (offset from zero by 2.5 cm/sec). (c) Observations from Garzoli and Katz (1983).

E. Low-frequency Variability of the Double-gyre Circulation: Numerical and Observational Results

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Understanding the basic dynamical behavior of Western Boundary Currents (WBCs) plays an important role in setting up proper models for assimilating data and predicting the North Atlantic Basin's (NAB) wind-driven circulation. Low-frequency variability of WBCs, along with their separation and associated eastward jets, are key dynamical issues that have recently received increasing observational and theoretical attention. The numerical simulation of the wind-driven, double-gyre ocean circulation in a closed basin illustrates the nonlinear behavior of WBCs depending on three parameters, i.e., the magnitude of wind stress, viscosity and basin size. A systematic study, using continuation techniques that explore the parameter space of the model, provides an exhaustive picture of the model's dynamical behavior. It also gives insight into the physics governing the transitions from multiple equilibria (Figs. 7a, b) to periodic (Fig. 8a) and to weakly chaotic (Figs. 8a, b) solutions. The periods dominating the periodic and aperiodic solutions vary from 1.3 to 6.5 years depending on parameter values.

In order to compare the results of the simulations to the observed circulation of the North Atlantic and North Pacific basins, and to explore any other interannual variability of the mid-latitude oceanic basins, the analysis of relatively long observational datasets was performed by using Singular Spectrum Analysis. Preliminary results on the Comprehensive Ocean-Atmosphere Data Set (COADS) Sea Surface Temperature (SST) fields (for the time interval 1970-1993), reveal the existence of an interannual oscillatory mode in the North Pacific Ocean, whose period is 28 months. This mode does not show any significant correlation with El Niño interannual variability. In the analysis carried out for the SST field of NAB, two interannual modes, periods around 20 months and 6 years respectively, are identified. Both peaks are also found in the results of our simulations for a rectangular basin of NAB size.

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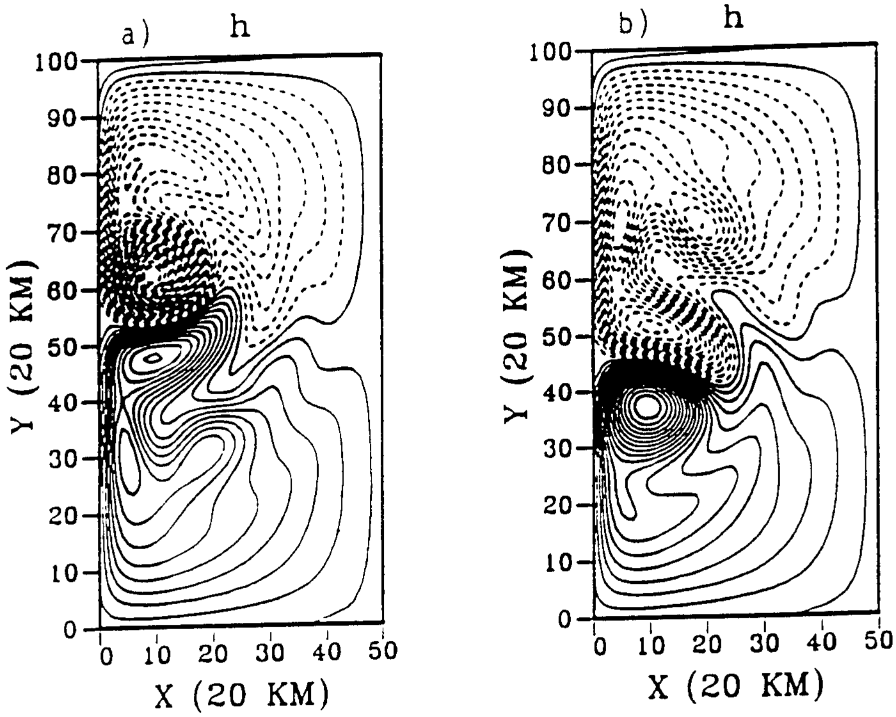

Figure 7: The instantaneous upper-layer thickness (ULT) plots for multiple steady states. Solid (dashed) lines stand for ULT~ 500 m (ULT< 500 m) with contour interval of 5 m.

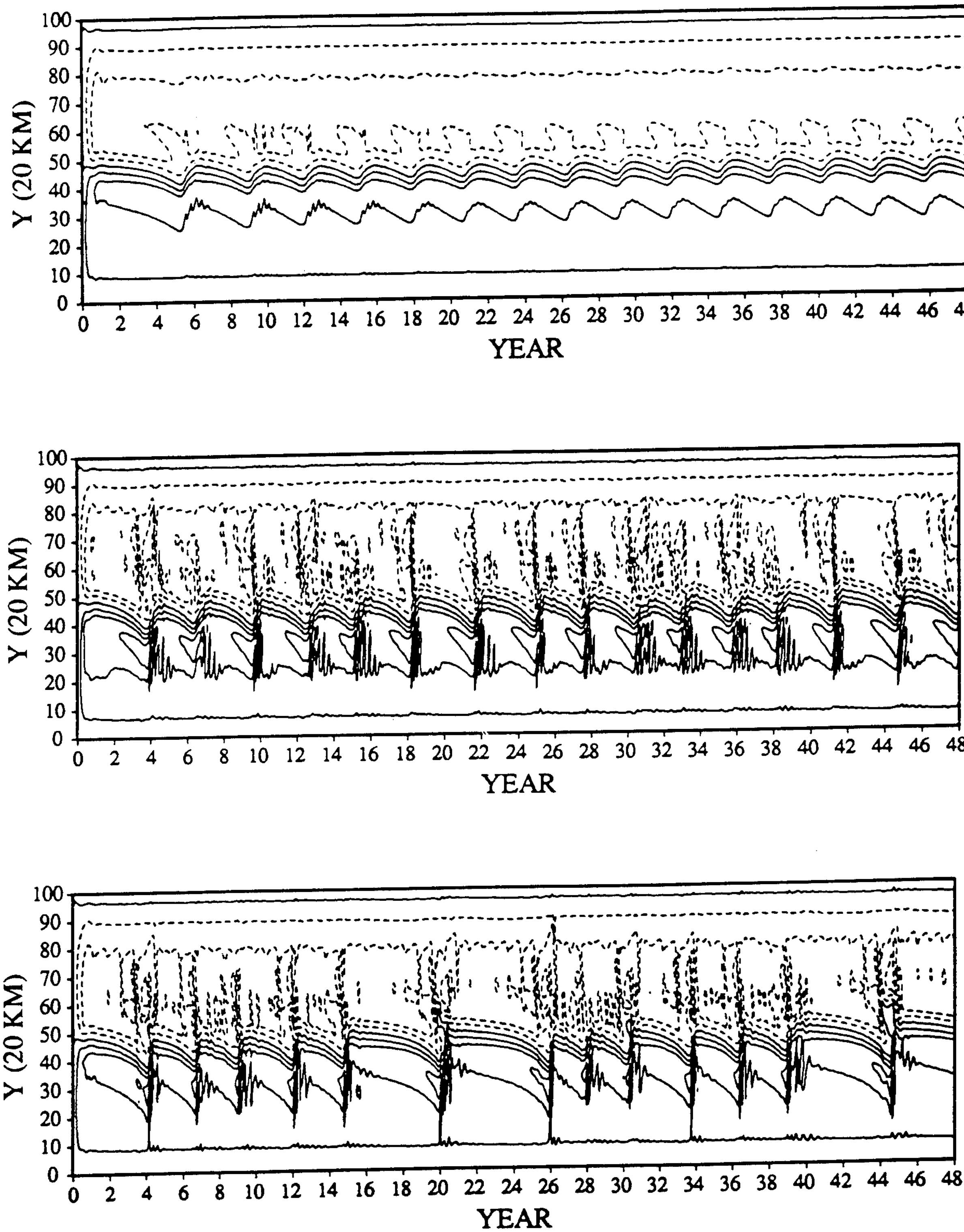

Figure 8: 48-year evolution of ULT along 2 = 80 km for (a) periodic, (b) aperiodic, and (c) period-doubled oscillations. Contours as in Fig. 7; contour interval is 20 m.

F. NRL Effort in the North Atlantic

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The NRL group plans to use the Navy Layered Ocean Model with 1/4°, 1/8° and 1/16° resolution and about 6-layers in the vertical. Both DAMÉE domains (9°N-47°N and 20°S-65°N) and both hydrodynamic and thermodynamic versions of the model will be used. Hydrodynamic simulations with up to 1/8° resolution and 6 layers have been integrated to statistical equilibrium on the larger DAMÉE domain driven by the Hellerman and Rosenstein wind stress climatology. In addition, a 1/8°, 6-layer global model, spun up to equilibrium at 1/4°, was integrated for two years on the CRAY C90 at CEWES. A snapshot of sea surface height over the larger DAMÉE domain at the end of this run is shown in Figure 9. The current pattern over the subarctic gyre is in close agreement with one presented by Lazier and Wright (1993), including the loop in the North Atlantic current, its bifurcation further to the east and its passage east of the Flemish Cap. The Gulf Stream shows a realistic path between Cape Hatteras and the Grand Banks in this snapshot, but a longer integration is required to see if this is a robust result. Only limited-area Gulf Stream models have been successful in robustly simulating a realistic mean path for the Gulf Stream (e.g. Thompson and Schmitz, 1989; Schmitz and Thompson, 1993). At this writing, the 1/8° global simulation has just started running on the CM5 at NRL.

Thompson et al., (1992) presented results from a 1/4°, 4-layer Atlantic model which showed a realistic mean and seasonal cycle for the transport between Florida and the Bahamas north of the Northwest Providence Channel (Fig. 10). The model was driven by ECMWF 1000 mb winds with the 1981-1989 mean replaced by the annual mean from Hellerman-Rosenstein. A 13 Sv thermohaline circulation was input at the boundary using values from Schmitz and Richardson (1991). However, when errors in the ETOPO-5 topography were corrected in the Bahamas and the vertical mixing scheme was improved, the mean transport dropped to about 23 Sv, and there was too much flow east of the Bahamas (Fig. 11a, b). Additional corrections to the topography, especially in the southeast Bahamas, returned the Florida Strait transport and the flow east of the Bahamas to realistic values (Fig. 11d). Data assimilation and forecasting studies done for the Atlantic so far have used a 2-layer limited-area Gulf Stream model (Fox et al., 1992; Fox et al., 1993; Smedstad and Fox, 1994).

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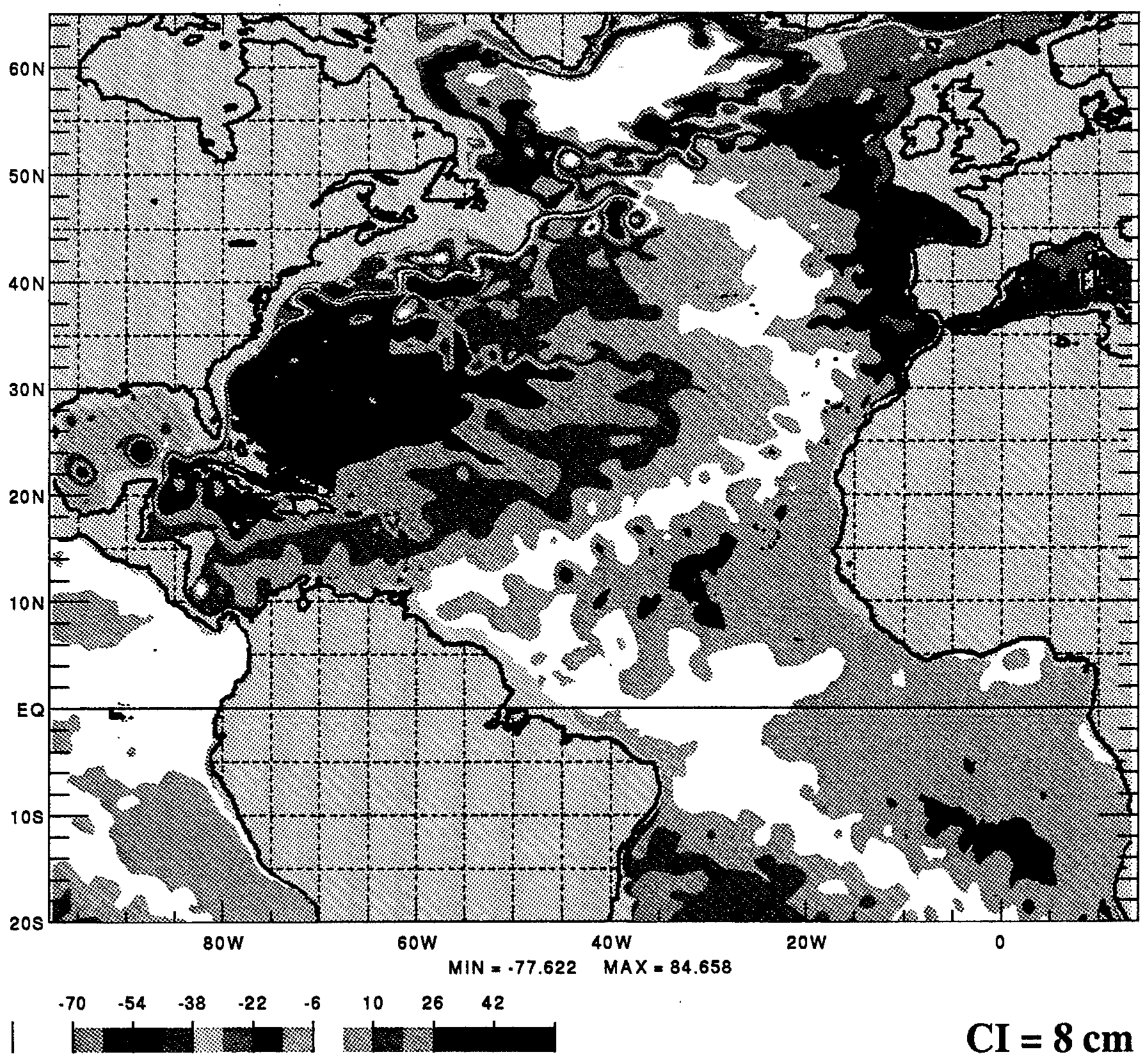
Fig. 9. Sea surface height (cm) snapshot from a 1/8°, 6-layer global ocean model with realistic bottom topography driven by the Hellerman-Rosenstein (1983) monthly wind stress climatology.



CI = 8 cm

Fig. 10. Annual cycle of volume transport of the Florida Current at 27°N from the Subtropical Atlantic Climate Studies Program (STACS) (courtesy Jimmy Larsen, NOAA/PMEL), from two different model simulations driven by the same 8-year time series of European Centre for Medium-Range Weather Forecasts wind forcing and from a model simulation forced by the Hellerman-Rosenstein (1983)monthly wind stress climatology.

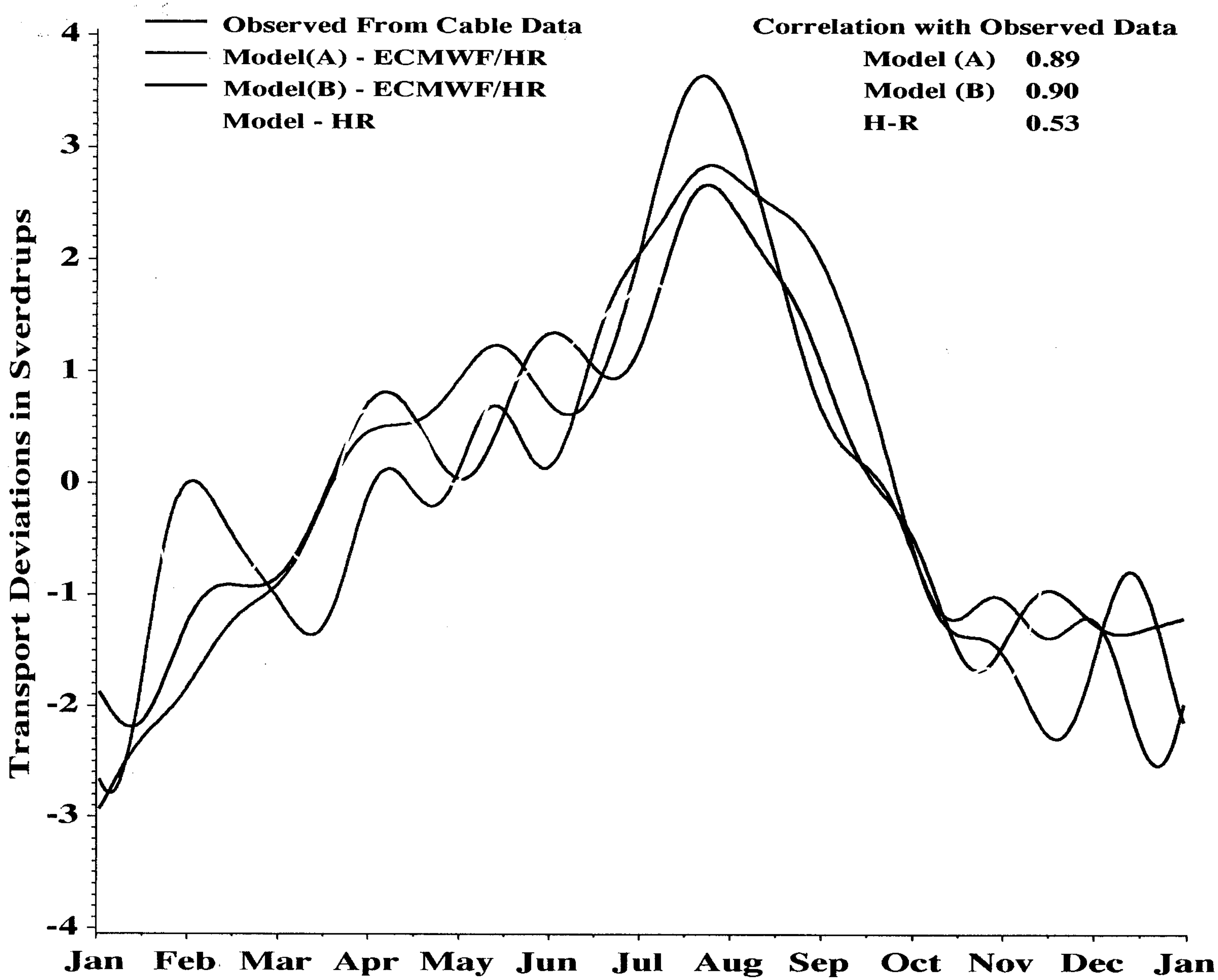
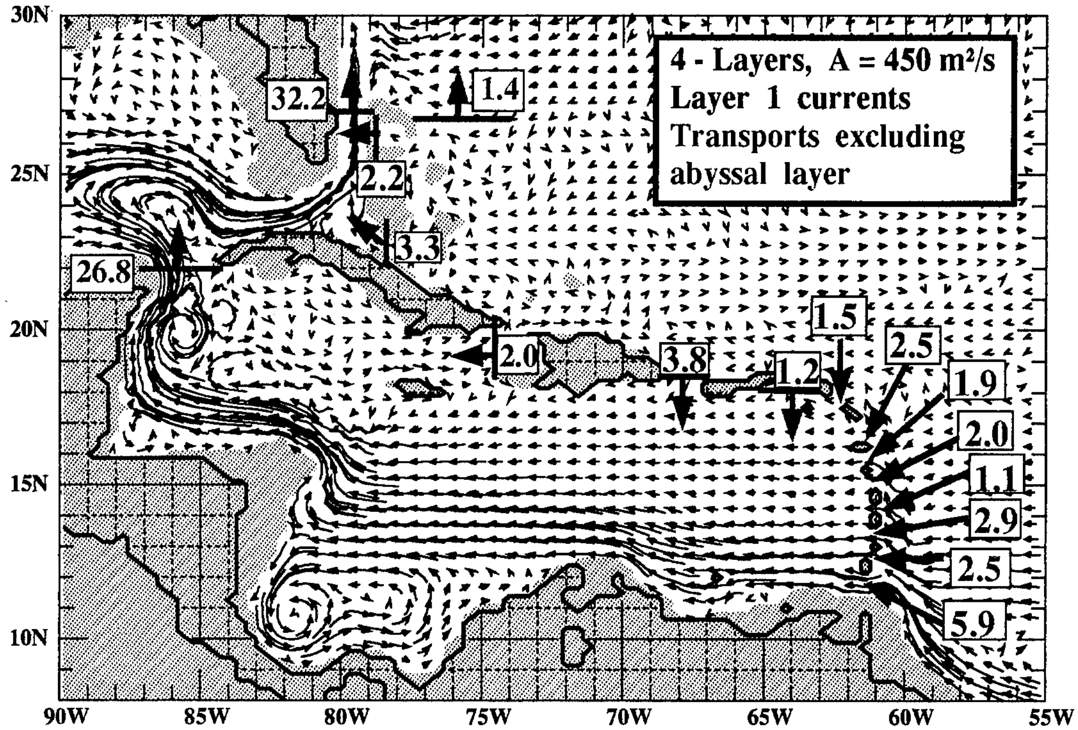


Fig. 11. Simulated Mean Currents and Transports Through the Intra-Americas Sea as a Function of Changes in Atlantic Ocean Model Geometry

a. Geometry Dana Thompson used in Florida Straits Cable Data comparison



b. Improved geometry and vertical mixing scheme

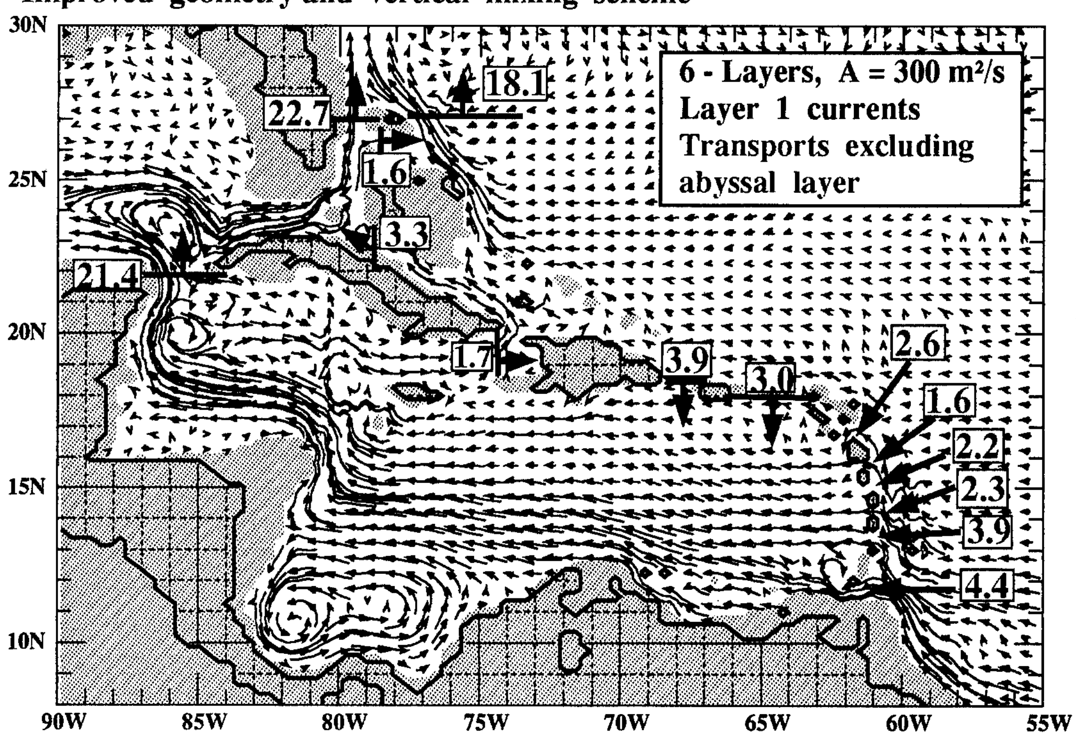


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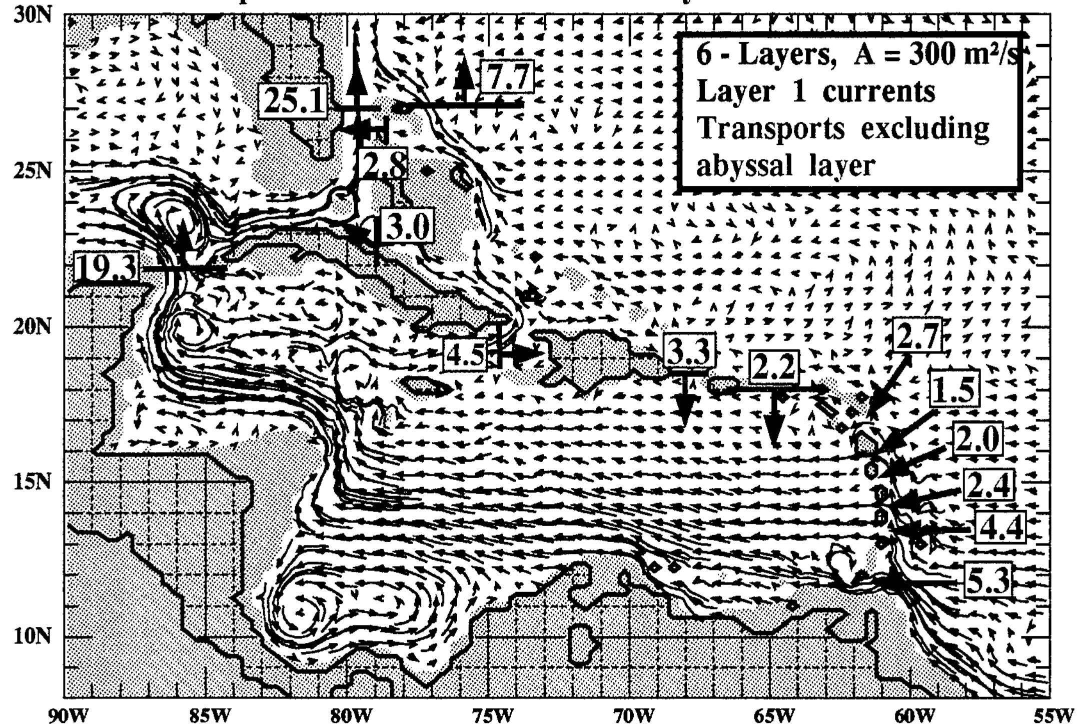
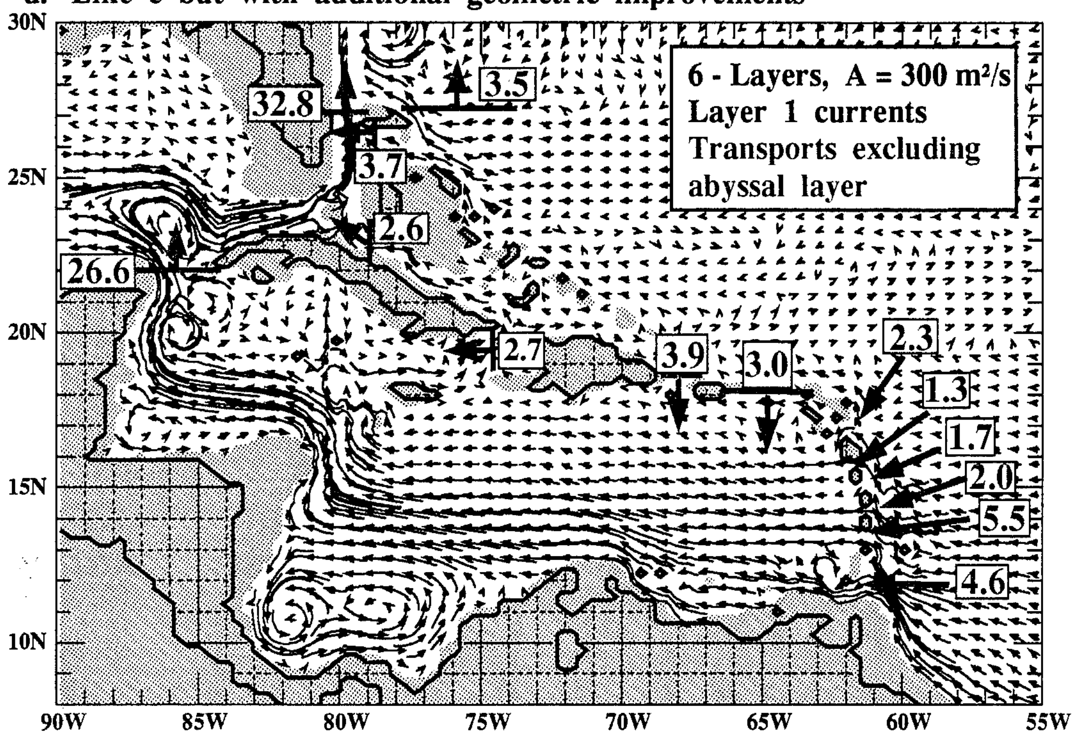
Fig. 11. Simulated Mean Currents and Transports Through the Intra-Americas Sea as a Function of Changes in Atlantic Ocean Model Geometry

c. Like b except for eastern Florida boundary



d. Like c but with additional geometric improvements



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A preliminary experiment plan is presented for Data Assimilation and Model Evaluation Experiments -- North Atlantic Basin (DAMEE-NAB). The plan describes the approach to implement a comparative environment in which to assess numerical ocean model nowcast/forecast capabilities and data assimilation methods and techniques. Goals are stated which provide direction for the long term, the next five years, and specifically for the next two years. A design of the experiment is outlined in terms of domain, data requirements, and measures of performance. The plan will be refined over the next year and will be allowed to evolve as the experiment proceeds. A brief description by participants of models and data assimilation methods are included.

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